Probing Interlayer Exchange Hardening Interactions With The X-Ray Magneto-Optical Kerr Effect

J.B. Kortright,[1] Sang-Koog Kim,[1] E.E. Fullerton,[2] K. Takano,[2] J.S. Jiang,[3] and S.D. Bader[3]
[1]Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720
[2]IBM Almaden Research Center, San Jose, California 95120
[3]Materials Sciences Division, Argonne National Laboratory, Argonne, Illinois 60439

INTRODUCTION

Exchange hardening refers to interactions between two magnetic phases to yield a superior composite, and provides one route to new hard (permanent) magnet materials with increased stored energy product [1], a figure of merit roughly proportional to the saturation magnetic moment times the coercive field. Because permanent magnets are ubiquitous in the technology that generates and utilizes electricity, improved permanent magnets can lead to substantial efficiencies in energy usage. Typically materials with high magnetic moment have low coercivity (low magneto-crystalline anisotropy) while high coercivity (anisotropy) materials often have low saturation moment. The goal of exchange hardening is to utilize interfacial exchange interactions between finely dispersed (nano-scale) hard and soft phases to realize these improved properties.

Most experimental techniques that measure the magnetic response of composite exchange hardening systems measure the net or aggregate response of the entire sample. A more complete understanding of these heterogeneous systems would be obtained by utilizing techniques that can follow the magnetization reversal of the hard and soft phases individually. By resolving the response of the individual phases, important details of how magnetic exchange interactions and microstructural changes affect each phase and thus contribute to the aggregate response of the composite can be learned. The element-specificity of resonant magneto-optical effects near core levels in the x-ray range offers numerous opportunities to study the magnetism in different phases.

HARD/SOFT EXCHANGE SPRING BI-LAYER SYSTEMS

We have begun to apply our newly developed magneto-optical Kerr and Faraday rotation techniques to study the responses of individual phases in model exchange hardening systems known as exchange-spring magnets [2,3]. These quasi-epitaxial layered structures grown by sputter deposition consist of bi-layer exchange couples. Typically a textured polycrystalline soft layer, Fe in our case, is grown on top of a hard Sm-Co layer that exhibits a significant degree of epitaxy and also some disorder in the form of some chemical heterogeneity. Exchange coupling at the Sm-Co/Fe interface results in significant changes in the properties of both the hard and soft layers, and by adjusting the thickness of each layer the composite response can vary widely between that of the two layers individually.

In a certain range of Fe and Sm-Co thickness interesting magnetic behavior is observed leading to the term exchange-spring structure. For Fe thickness comparable to or greater than the exchange stiffness length, as a demagnetizing field is applied along the easy axis, the top region of the Fe layer reverses magnetization first while the bottom of the Fe layer remains pinned in the opposite direction by the exchange coupling at the interface. While this situation persists a domain wall exists in the soft Fe layer parallel to the interface. Across this domain wall Fe spins rotate coherently by 180º parallel to the wall (Bloch wall) to form a spiral or twisted spin structure in depth. As the demagnetizing field increases this domain wall is compressed and pushed toward the Sm-Co layer until at some high value this twist is pushed through the interface into the hard layer as the entire structure reverses. At fields below this irreversible switching of the hard layer, the magnetization spiral in the soft Fe layer is entirely reversible, leading to the term spring magnet because the moment will spring back to the original direction over a considerable range.

A simple one-dimensional model of this exchange spring behavior has been developed and shown to fit measured magnetometry data quite well [2,3]. Since most of the magnetic moment in these samples results from the soft Fe layer, the measured data and success of the model in fitting the data primarily apply to the reversal of the soft Fe layer. Indeed some discrepancy exists at the irreversible field where the hard layer reverses, with measurements showing a broader range of reversal than does the model. Thus measurements of the reversal in both the soft Fe and hard Sm-Co layers are of interest to better understand the applicability of this simple one dimensional theoretical model. Of interest is the extent to which the reversal of each layer conforms to the predictions for that layer, and especially how spins in each layer near the interface are influenced by the presence of the layer across the interface having very different anisotropy. Questions of interest include, for example; how many hard layer spins reverse at fields below the irreversible field in response to Fe spins above, and likewise how many Fe spins remained pinned until the hard layer switches?

XMOKE STUDIES OF THE MAGNETIZATION TWIST IN THE FE LAYER

We are using element-resolved soft x-ray magneto-optical Kerr effect (XMOKE) hysteresis loops to follow ther reversal of each layer individually [4]. By tuning near the Fe $L_{2,3}$ edges XMOKE loops measure the response of just the Fe in the soft layer, while tuning near the Co $L_{2,3}$ edges yields the rotation of the Co in the hard layer. Measurements effectively utilize the intensity of linearly polarized undulator beamline 8.0 to measure Kerr rotation (in reflection) at different grazing incidence angle θ to vary the penetration depth into the sample.

Figure 1 shows the geometry of the measurement and some calculations simulating the intensity of the total electric field in the sample for a series of θ values. These calculations are made using realistic values of optical constants just below the Co L_3 edge, and reveal that only at relatively

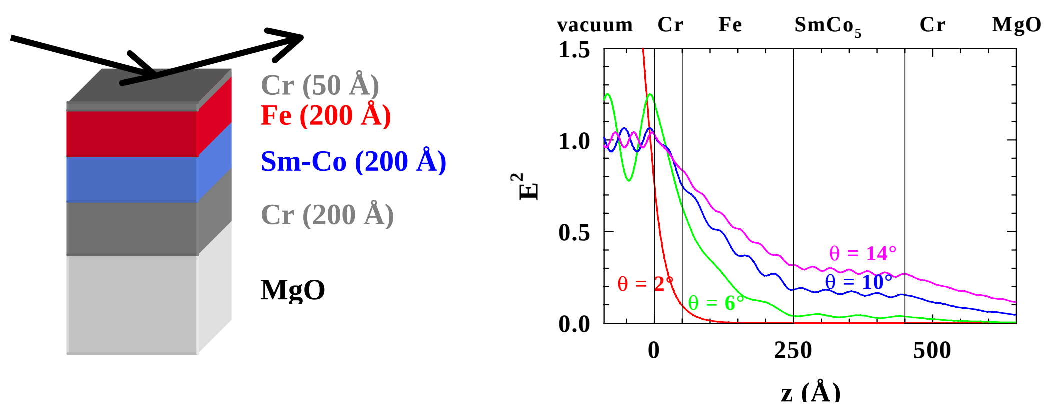

Figure 1. A spring-magnet structure is shown schematically at left consisting of a 20 nm Fe layer grown atop a 20 nm Sm-Co layer. The Cr cap layer prevents oxidation of the magnetic structure while the Cr underlayer seeds epitaxial growth. At right are calculations of the total electric field intensity vs. depth into this structure for a series of grazing incidence angles θ.

high grazing incidence angle does a significant field penetrate into the hard Sm-Co layer. Likewise these simulations show that by varying θ the field in the Fe layer can be varied so that just the top of this layer is sensed at small θ, and deeper regions of the Fe layer contribute to measured signals increasingly with θ. Thus one approach to obtaining depth-resolved information about magnetization is simply by varying incidence angle and measuring magneto-optical signals.

Early XMOKE data taken near the Fe L_3 edge at θ = 5° are shown in Figure 2. A longitudinal field varied along the easy axis yield these data from the reflected (Kerr) intensity and the rotation intensity measured after a linear polarizer placed in the reflected beam. The top of the Fe layer begins to switch at roughly 0.1 T while the irreversible field corresponding to the switching of the Sm-Co layer is roughly 0.6 T. At intermediate demagnetizing fields a reversible spin spiral structure exists in the Fe layer, as revealed in these data. The top panel shows the measured intensity after the linear polarizer that is sensitive both to polarization and intensity changes in the reflected beam. The middle panel shows the Kerr intensity measured before the polarizer that is insensitive to polarization changes on reflection. Dividing the top by the middle intensity yields the bottom panel showing the Kerr rotation angle. This Kerr angle is primarily sensitive to changes in the longitudinal component of the Fe moment, while the Kerr intensity signal is sensitive to changes in Fe moment transverse to the propagation direction. Such transverse components are necessarily associated with the coherent rotation of Fe spins that exist within the domain wall formed in the reversible field region. Data collected at different angles show systematic trends with θ.

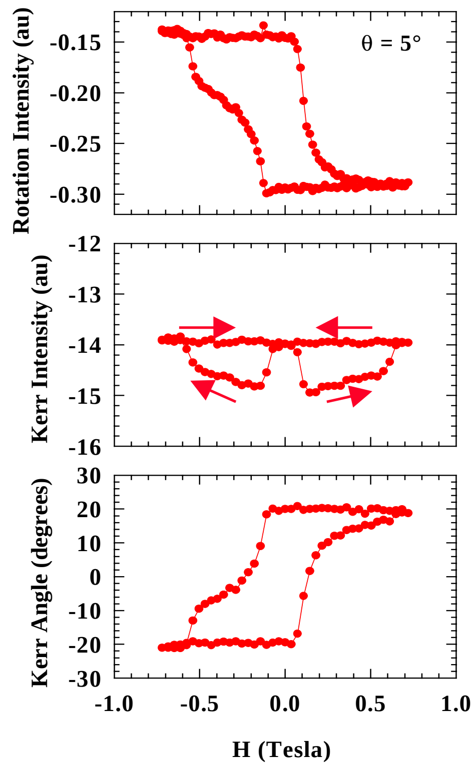

Figure 2. XMOKE hysteresis loop data measured several eV below the Fe L_3 edge for the model exchange spring structure depicted in Figure 1. Intensity measured after the linear polarizer (top), divided by Kerr intensity measured before the linear polarizer (middle), yields the Kerr angle (bottom).

By careful analysis of these XMOKE data we can thus learn about the three dimensional vector behavior of magnetization vs. depth within the Fe layer. We are implementing the magneto-optical formalism of Zak, *et al.*, [5] to calculate the magneto-optical Kerr response from an arbitrary magnetization structure in depth into the sample. We expect to be able both to test the model predictions of magnetization in this structure, and possibly determine a best experimental profile for the depth-variation of magnetization into the Fe layer.

Initial efforts to measure Co XMOKE loops in this sample were unsuccessful because of its large roughness resulting from the MgO substrate [6]. This sample's roughness is greater than the x-ray wavelenghts used and reduces the reflected signal by several orders of magnitude compared to that observed for relatively smooth samples at the large θ values needed to ensure penetration into the Co layer. Indeed from smoother bi-layer structures of Fe on Co having similar thickness to this exchange spring sample we clearly see the reversal in the buried Co film, confirming that it is roughness of this specific sample that limits study of its hard layer reversal. Indeed roughness may be one source of discrepancy between the simple one-dimensional model and behavior of real samples. We have several ideas to obtain hard layer data on this and similar samples.

CONCLUSIONS AND FUTURE DIRECTIONS

It is clear from these and other data that by combining element-specificity and depth-penetrating capabilities of XMOKE and related soft x-ray magneto-optical techniques we can study magnetic interactions in nano-phase composite magnets through their effects on the constituent phases. These unique capabilities should impact our understanding of many important problems in heterogeneous magnetic structures of increasing interest from fundamantal and applied perspectives.

These model exchange spring structures, whose magnetization reversal is complex yet thought to be reasonably well understood, are ideal systems to study as we move from the development of new x-ray magneto-optical techniques into their application to study important problems in magnetic materials. With continued effort we expect to be able to more rigorously test existing models describing magnetic exchange interactions in these structures than can current experimental techniques. By developing an understanding of the reversal in the hard and soft layers of model spring magnet systems, we will be well-positioned to apply these techniques to systems that may be less structurally perfect and whose behavior is less easy to predict and also less easy to understand experimentally. Exchange hardening composites exhibiting more disorder are important because they are more easily produced than epitaxial structures, and hence are good candidates for practical materials based on the exchange-hardening concept.

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Principal Investigator: Jeff Kortright, Materials Sciences Division, Lawrence Berkeley National Laboratory, Email:jbkortright@lbl.gov, Telephone: 510-486-5960.